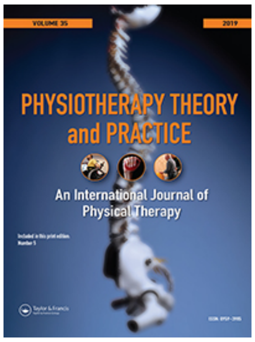

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CASE REPORT

Magnetic-resonance-imaging-based three-dimensional muscle reconstruction of hip abductor muscle volume in a person with a transfemoral bone-anchored prosthesis: A feasibility study

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ABSTRACT

Background: Persons with transfemoral amputation typically have severe muscle atrophy of the residual limb. The effect of bone-anchored prosthesis use on existing muscle atrophy is unknown. A potentially feasible method to evaluate this is magnetic resonance imaging (MRI)-based three-dimensional (3D) muscle reconstruction. We aimed to (1) examine the feasibility of MRI-based 3D muscle reconstruction technique in a person with a cobalt–chrome–molybdenum transfemoral bone-anchored prosthesis; and (2) describe the change of hip abductor muscle volume over time. **Methods**: In this single case, 1-year follow-up study we reconstructed the 3D hip abductor muscle volumes semiautomatically from MRI scans at baseline, 6- and 12-month follow-up. The number of adverse events, difficulties in data analysis, time investment and participants' burden determined the level of feasibility. **Results**: We included a man (70 years) with a transfemoral amputation who received a bone-anchored prosthesis after 52 years of socket prosthesis use. No adverse events occurred. The accuracy of the 3D reconstruction was potentially reduced by severe adipose tissue interposition. Data analysis was time-intensive (115 h). Participants' burden was limited to 3-h time investment. Compared to baseline, the total hip abductor volume of both the residual limb (6 month: 5.5%; 12 month: 7.4%) and sound limb (6 month: 7.8%; 12 month: 5.5%) increased. **Conclusion**: The presented technique appears feasible to follow muscle volume changes over time in a person with a cobalt–chrome–molybdenum transfemoral bone-anchored prosthesis in an experimental setting. Future research should focus on analysis of muscle tissue composition and the feasibility in bone-anchored prostheses of other alloys.

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Amputees; osseointegration; artificial limbs; magnetic resonance imaging; three-dimensional reconstruction

Introduction

Hip abductor muscle strength is lower in the residual limb in persons with a transfemoral amputation compared to the sound side and to healthy subjects (Bae, Choi, Hong, and Mun, 2007; Kowal and Rutkowska-Kucharska, 2014; Ryser, Erickson, and Cahalan, 1988). Muscle strength weakness of the thigh is associated with the presence of muscle atrophy (Klingenstierna, Renstrom, Grimby, and Morelli, 1990; Renstrom, Grimby, and Larsson, 1983). Muscle atrophy is present in the residual limb, and can be as high as 73%, despite the almost continuous activation of the hip muscles during gait, which presumably is needed to stabilize the stump in the socket and to stabilize the pelvis (Jaegers, Arendzen, and De Jongh, 1995b, 1996; Renstrom, Grimby, Morelli, and Palmertz, 1983; Wentink, Prinsen, Rietman, and Veltink, 2013). Muscle tissue composition changes as a result of the amputation, as cleaved muscles that are not fixed retract and degenerate into adipose tissue (Jaegers, Arendzen, and De Jongh, 1995b). Inferior and asymmetric muscle strength and high levels of muscle atrophy are associated with an asymmetric gait pattern, such as increased trunk lateral bending toward the prosthetic side and an unstable pelvis during stance (Jaegers, Arendzen, and De Jongh, 1995a, 1995b,

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1996; Michaud, Gard, and Childress, 2000; Nadollek, Brauer, and Isles, 2002; Sjodahl, Jarnlo, Soderberg, and Persson, 2003). The current method for the attachment of a prosthesis after a transfemoral amputation is using a prosthetic socket. The socket attachment is, however, associated with chronic skin problems and residual limb pain (Butler et al, 2014). These socket-related problems can lead to limited prosthetic use and decreased Health-Related Quality of Life (HRQoL) (Hagberg and Branemark, 2001).

Bone-anchored prosthetics is a promising method to attach the prosthesis directly to the human skeleton, which can be a solution for persons suffering from socket-related problems (Pitkin, 2013). It has been shown that the use of bone-anchored prostheses is associated with increased prosthetic use, a higher activity level and a better HRQoL relative to socket attached prostheses (Leijendekkers, et al., 2017). In contrast to the socket attachment, which can be used for passive stabilization during the stance phase of gait, persons with bone-anchored prostheses are forced to stabilize their residual limb and pelvis solely by means of their residual limb muscles. Persons with bone-anchored prostheses present more physiological muscle activity in the residual limb, and better hip and pelvic kinematics compared to persons with socket attached prostheses (Pantall and Ewins, 2013; Tranberg, Zugner, and Karrholm, 2011). These benefits, combined with the absence of external compression on the residual limb muscles may, in theory, result in preservation of muscle volumes, muscle tissue composition and a more symmetric gait pattern.

To date, there has been no evaluation of muscle volumes or muscle tissue composition in persons with a bone-anchored prosthesis. It is unknown whether the muscle changes, caused by wearing a socket prosthesis, are reversed by using a bone-anchored prosthesis. To study this, repeated three-dimensional (3D) muscle reconstruction based on magnetic resonance imaging (MRI) can be utilized in persons after implantation of a bone-anchored prosthesis. Jaegers, Arendzen, and De Jongh (1995b) used this volumetric measurement technique successfully despite the changed geometry of some muscles and the presence of transected muscles in a cross-sectional study including persons with a transfemoral amputation who used a socket attached prosthesis. It is unknown whether this procedure is applicable in persons with a bone-anchored prosthesis since metal implants can cause artifacts that may hinder exact evaluation of muscle measurements (Panfili et al., 2014).

In this single case, 1-year follow-up study with repeated measures we used an MRI-based 3D muscle reconstruction technique to evaluate hip abductor muscle volume in a person after receiving a transfemoral cobalt–chrome–molybdenum bone-anchored prosthesis. The primary aim of this study was to examine the feasibility of an MRI-based 3D muscle reconstruction technique. Our secondary aim was to describe the change of hip abductor muscle volume in the first year after implantation of a transfemoral bone-anchored prosthesis.

Methods

A comprehensive description of the participant, surgery, 12-week rehabilitation program and clinical outcomes, including hip abductor muscle strength obtained by hand-held dynamometry and self-reported walking distance in everyday life has already been reported elsewhere (van Hinte, Nijhuis-van der Sanden, and Staal, 2017). Consequently, only the most relevant information will be presented here. The baseline assessment to collect the participants' demographic and anthropometric characteristics and the clinical outcomes was conducted 2.5 weeks prior to the first surgery. The bone-anchored prosthesis was implanted in a two-step surgery, 6 weeks apart. The baseline MRI was made 5 weeks after the first surgery, including implantation of the intramedullary implant (Figure 1). One week later the second surgery was executed in which a soft tissue stoma was created and a transcutaneous connector (Figure 1) was bolted into the intramedullary stem. Rehabilitation started 2 weeks after the second surgery. The prosthetic parts were attached to

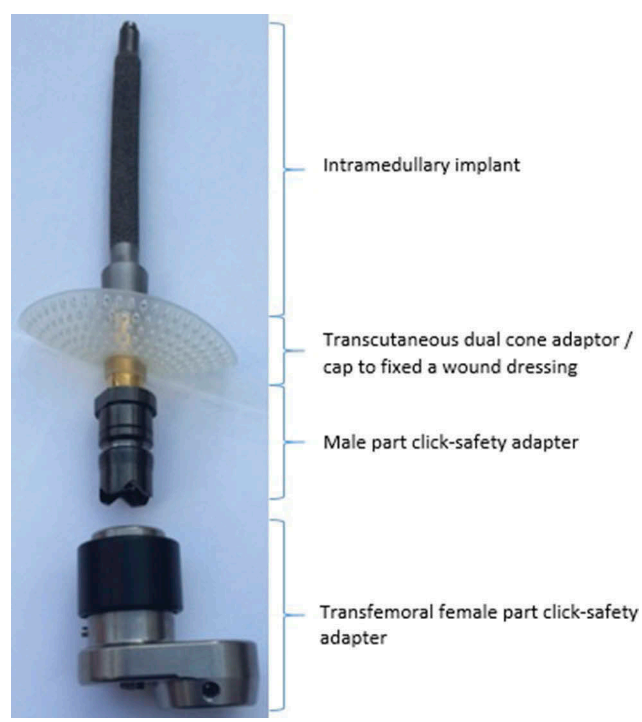

Figure 1. Bone-anchored prosthesis and click-safety adapter.

the transcutaneous unit using a stainless steel click-safety adapter (OTN, Nijmegen, Netherlands). The timing of the baseline MRI was chosen aiming at equal geometry of the soft tissue at all assessments in order to prevent measurement bias due to soft tissue modification which often is included in the first surgery. The two follow-up MRI scans were made 6 and 12 months after the first MRI. At the follow-ups the stainless steel male part of the click-safety adapter (Figure 1) was removed before MRI scanning, in order to reduce the amount of artifacts and to avoid overheating the metallic parts outside the body.

The study was conducted according to the principles of the Declaration of Helsinki (64th version, 19–10–2013). The protocol of this study was approved by the Ethics Committees of Radboud University Medical Centre.

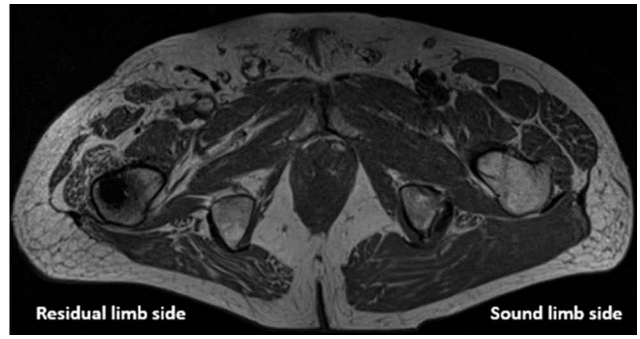

Figure 2. Transverse plane MR image at baseline.
Note: the presence of severe adipose tissue on the residual limb side compared to the sound side.

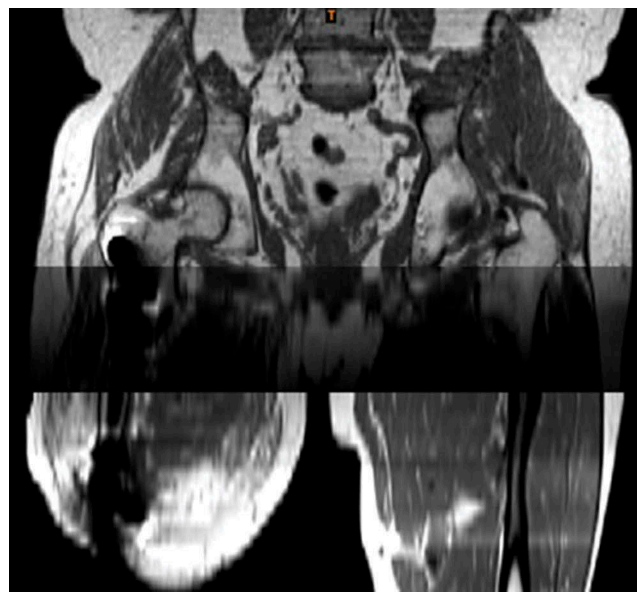

Figure 3. Coronal plane MR image at baseline.
Note: the presence of metal artefacts at the distal end of the residual limb and the abrupt transition between adjacent stacks after combining the MR volumes.

Feasibility

The level of feasibility of the MRI-based 3D muscle reconstruction technique was determined through evaluation of various aspects of the procedure. First, adverse events during the MRI sessions such as loosening and migration of the intramedullary implant/transcutaneous connector, heating of the metal with surrounding tissue, thermal damage and injuries due to physical contact with the MRI scanner as result of ferromagnetism of the implant were noted when observed by the participant or the caregivers (Kumar et al., 2006). Second, difficulties in data analysis, for example, due to limited or obscured visibility of the muscles, were documented after a verbal evaluation. Third, the time investment for data collection and analysis was recorded. Lastly, participants' burden in terms of time investment and discomfort was verbally evaluated after each assessment.

Volume measurement

A Siemens Magnetom 1.5 Tesla (T) MRI scanner (Siemens medical systems, Malvern, PA, USA) was used to obtain transverse images (Figure 2) of the lower body from the upper edge of the cresta iliaca to the tibial tuberosity in the supine position. The scan protocol was based on previous research by Scheys in order to yield optimal distinction of muscle boundaries and to reduce metal artifacts (Scheys, 2009). We used T1-weighted images (with a repetition time of 600 ms, echo time of 7.7 ms, slice thickness of 3.3 mm, flip angle of 150°, and an in plane resolution of 1 mm × 1 mm). The region of interest was scanned in three successive series, with an overlap of at least two slices between series. The image stacks produced were combined into a single volume (Figure 3) using Mimics software (Version 18, Materialise N.V., Leuven, Belgium) (Kolk et al., 2015).

Muscle volume of the hip abductor muscles (*m. gluteus maximus, m. gluteus medius, m. gluteus minimus, m. piriformis, and m. tensor fasciae latae*) were segmented and calculated using Mimics. The procedure to analyze the baseline MRI of the residual limb and sound limb was different. For the residual limb, the abductor muscles were outlined manually slice-by-slice, and with optional use of a threshold tool for inclusion of voxels with a predefined grey value (159–388). The regions of interest were first analyzed in the transverse plane and checked, thereafter, also in the sagittal and coronal plane. This procedure resulted in

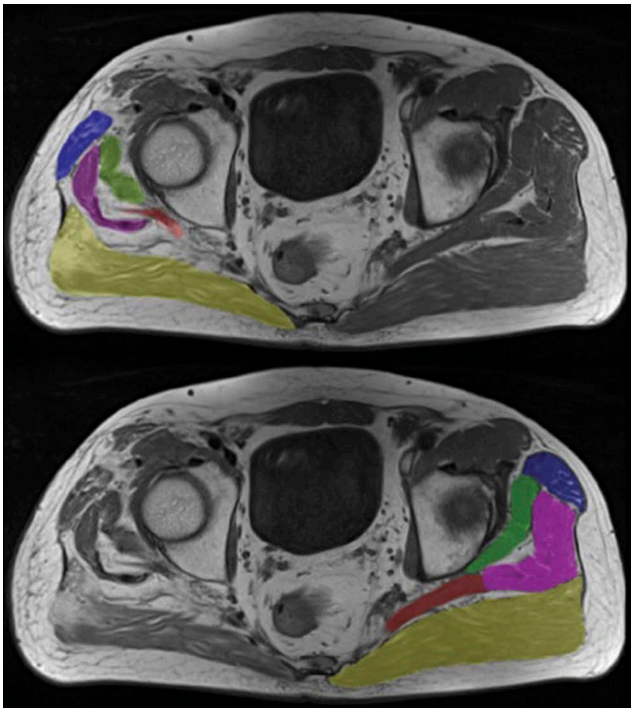

Figure 4. Tailored atlas of the residual limb (above) and sound limb (below) at baseline.
Note: M. gluteus maximus (yellow), m. gluteus medius (purple), m. gluteus minimus (green), m. piriformis (red) and m. tensor fasciae latae (blue).

a tailored reconstruction of all muscles of interest, hereafter called "atlas" (Figure 4). For the segmentation of the sound limb, an existing set of 10 atlases was used as starting point, which was based on the MRI scans of 10 healthy subjects (Kolk et al., 2015). These 10 atlases and the Mimics software were used to semi-automatically segment the hip abductor muscles of the sound limb, following the procedure described by Kolk et al. (2015). The follow-up MRI scans were segmented semi-automatically using the baseline tailored atlases previously obtained for the sound and residual limbs. The Mimics feature "Calculate 3D" was then applied to all atlases to reconstruct the final 3D muscle geometries. No additional smoothing was applied, to not arbitrarily alter the volume reconstructions. Individual muscle volumes (in units of cm^3) were calculated from the 3D muscle geometries (Figure 5) using Mimics.

The baseline MRI of the residual side was manually segmented by a student (TB). An engineer (LD) processed all segmentations. In the presence of debate about the exact muscle boundaries, a consensus meeting with three raters, radiologist (MP), engineer (LD), and physiotherapist (RL) established consensus about the exact muscle boundaries.

Data analysis

On the residual and sound limb the muscle volume of the final 3D geometries of *m. gluteus maximus, m. gluteus medius, m. gluteus minimus, m. piriformis, and m. tensor fasciae latae* were presented separately for the baseline assessment and for the 6- and 12-month follow-ups. The volume changes between follow-ups and baseline were calculated and expressed in percentages. Additionally, the difference in volume between sound

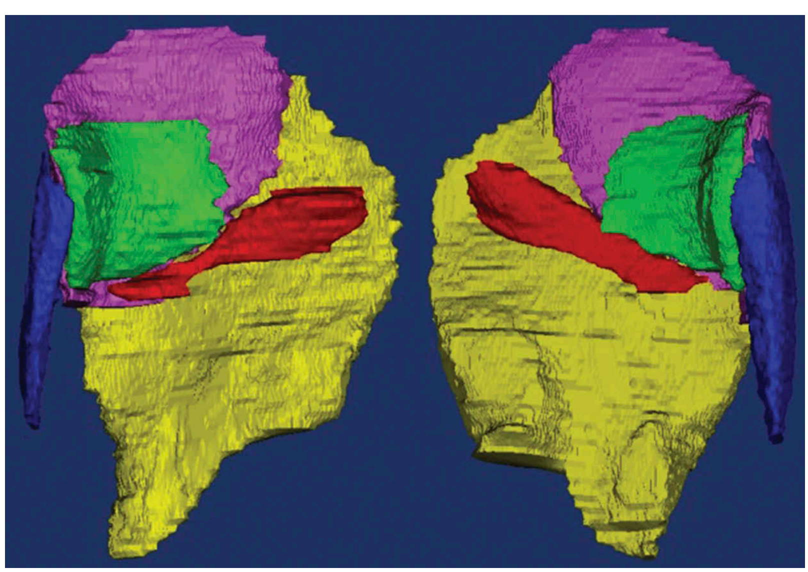

Figure 5. Final 3-D reconstruction hip abductor muscles of the residual limb (left) and sound limb (right) at baseline.
Note: M. gluteus maximus (yellow), m. gluteus medius (purple), m. gluteus minimus (green), m. piriformis (red) and m. tensor fasciae latae (blue).

and residual limb was calculated within each assessment and expressed in percentages.

Results

Participant characteristics

A 70-year-old man (1.78 m) with a traumatic transfemoral amputation who underwent implantation of a cobalt–chrome–molybdenum endo-exo femoral prosthesis (EEFP) after 52 years of socket prosthesis use participated in this study. Body mass index (BMI) adjusted for limb loss (Osterkamp, 1995) was 28 kg/m^2 at baseline and 30 kg/m^2 at both follow-up times. In the residual limb, hip abductor strength reduced by 2.2% at 6-month follow-up compared to baseline and was comparable to baseline at 12-month follow-up. In the sound limb, hip abductor strength reduced by 13.6% and 16.6% compared to baseline at 6-month and 12-month follow-up, respectively. Walking distance in everyday life decreased by 50% at 6-month follow-up and increased by 400% at 12-month follow-up, compared to baseline. The participant reported severe low back pain at the 6-month follow-up from degenerative disc disease, which was treated successfully with an epidural steroid injection 10 months after the second surgery.

Feasibility

No adverse events, such as heating of the metallic parts, were reported by the participant or the caregivers. MRI artifacts were mainly present toward the distal end of the residual limb (Figure 3). These artifacts caused no difficulties in the 3D reconstruction of the hip abductor muscles because the region of interest was proximal to these artifacts. The visibility of the boundaries of the residual limb muscles was less clear compared to the sound limb, as a result of the adipose tissue interposition (Figure 2). Adipose tissue was present between muscles (intermuscular adipose tissue) and within the boundaries of muscles' *fasciae* (intramuscular adipose tissue). When adipose tissue was present in a large extent relative to the muscle volume, more discussion was necessary to reach consensus about the exact boundaries of the individual muscles. This was the case, for instance, of *m. piriformis* (Figure 4). The manual segmentation of the residual limb of the baseline MRI, the manual correction within the semiautomatic segmentation process, and the consensus meetings were time-intensive (approximately 115 h in total). No disagreement between the raters occurred within the three consensus meetings of 5 h that were necessary to established consensus about the exact muscle boundaries. Because the male part of the click-safety adapter (Figure 1) had to be removed during the MRI scan, a certified prosthetist of the treatment team had to be present during the MRI session, which caused some logistic challenges. Participants' burden consisted out of approximately 1-h time investment per MRI scan. The participant experienced no discomfort during the MRI sessions.

Muscle volume change

In the residual limb, individual hip abductor muscle volumes increased in the range of 2.2–22.4% at 6-month follow-up and 1.5–22.4% at 12-month follow-up relative to baseline. The volume of *m. piriformis* decreased by 8.9% at 12-month follow-up relative to baseline (Table 1). The total hip abductor muscle volume increased by 5.5% at 6-month follow-up and 7.4% at 12-month follow-up relative to baseline (Table 1 and Figure 6). In the sound limb, individual hip abductor muscle volumes increased in the range of 5.8–15.4% at 6-month follow-up and 1.9–6.3% at 12-month follow-up relative to baseline (Table 1). The total hip abductor muscle volume increased 7.8% at 6-month follow-up and 5.5% at 12-month follow-up relative to baseline (Table 1 and Figure 6).

The degree and the trend of asymmetry between residual and sound limb remained consistent over time (Table 1 and Figure 6). The total hip abductor muscle volume of the residual limb was 35%, 37%, and 34% lower than the total hip abductor muscle volume of the sound limb, at baseline, 6-month and 12-month follow-up, respectively. Within the individual muscles, we found the following trends (Table 1 and Figure 6), the asymmetry of *m. gluteus maximus and m. gluteus medius* increased at 6-month follow-up and decreased at 12-month follow-up compared to baseline. The asymmetry of *m. gluteus minimus* decreased and the asymmetry of the *m. piriformis* increased at both follow-ups relative to baseline. The asymmetry of *m. tensor fasciae latae* decreased at 6-month follow-up and increased at 12-month follow-up compared to baseline.

Discussion

The results of this study showed that the MRI-based 3D muscle reconstruction technique is feasible to assess hip abductor muscle volume in a person with a transfemoral cobalt–chrome–molybdenum bone-anchored prosthesis in an experimental setting. No adverse events were reported. MRI artifacts due to metal hardware did

Table 1. Hip abductor muscle volumes.

	Baseline (cm^3)	6 month (cm^3)	12 month (cm^3)	Difference T1–T0 (%)	Difference T2–T0 (%)
Residual limb					
m. gluteus maximus	716	736	762	2.8	6.4
m. gluteus medius	297	320	326	7.7	9.8
m. gluteus minimus	76	93	93	22.4	22.4
m. piriformis	45	46	41	2.2	−8.9
m. tensor fasciae latae	67	72	68	7.5	1.5
Total	*1201*	*1267*	*1290*	*5.5*	*7.4*
Sound limb					
m. gluteus maximus	1167	1235	1235	5.8	5.8
m. gluteus medius	422	471	444	11.6	5.2
m. gluteus minimus	85	96	87	12.9	2.4
m. piriformis	52	60	53	15.4	1.9
m. tensor fasciae latae	126	135	134	7.1	6.3
Total	*1852*	*1997*	*1953*	*7.8*	*5.5*
Difference residual limb versus sound limb (%)					
m. gluteus maximus	−38.6%	−40.4%	−38.3%		
m. gluteus medius	−29.6%	−32.1%	−26.6%		
m. gluteus minimus	−10.6%	−3.1%	6.9%		
m. piriformis	−13.5%	−23.3%	−22.6%		
m. tensor fasciae latae	−46.8%	−46.7%	−49.3%		
Total	*−35.2%*	*−36.6%*	*−33.9%*		

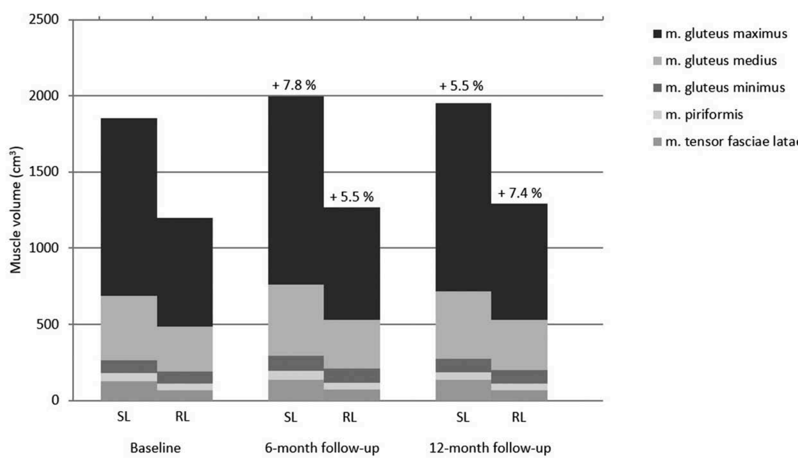

Figure 6. Total hip abductor muscle volume. Note: SL: sound limb; RL:residual limb.

occur, but they did not influence the 3D muscle reconstructions. The severe presence of adipose tissue hampered the exact volume measurements in some of the residual limb muscles, which may have led to measurement bias. Participants' burden was acceptable because it was limited to 3-h time investment (1 h per MRI scan), but both the need for technical support during the MRI scans and the time-intensive data analysis, decrease the feasibility in studies with a large sample size. We opted a 1.5T MRI scanner and an MRI protocol based on previous research (Scheys, 2009) in an attempt to achieve optimal distinction of muscle boundaries and concurrently reduce metal artifacts (Lazik et al., 2015; Nardo et al., 2015; Panfili et al., 2014). These choices were successful, as illustrated by the high image quality obtained (Figure 2) and the absence of image artifacts within the regions of interest (Figure 3). This is in line with studies in persons with a total hip arthroplasty (Lazik et al., 2015; Nardo et al., 2015). The MRI artifacts at the distal end of the residual limb were probably caused by the absence of bone in that area and the limited covering of the implant by soft tissue. Therefore, the MRI-based 3D muscle reconstruction technique will not be suitable to examine problems related to the soft tissue stoma.

In this single case study, the total hip abductor muscle volume asymmetry remained stable over time. The asymmetry ranged from 34 to 37% and was in favor of the sound side, which is comparable with the findings of Jaegers, Arendzen, and De Jongh (1995b). The total hip abductor muscle volume of both limbs increased at both follow-ups compared to baseline. The increase in muscle volume of the majority of the individual muscles exceeded the 1–3% intra-rater volume differences (interpretational error) of MRI-based 3D hip abductor muscle reconstruction (Jaegers, Dantuma, and De Jongh, 1992). These observations may indicate a possible reversion of the muscle atrophy process in a person with severe disuse muscle atrophy. Although larger studies are required to support this observation, this is the first description in reversibility of disuse-related muscle atrophy in a person with a transfemoral amputation using a bone-anchored prosthesis. Muscle volume at baseline in this case report is in line with the cross-sectional data of Jaegers, Arendzen, and De Jongh (1995b). Jaegers, Arendzen, and De Jongh (1995b) assessed muscle volume of the lower extremity using an MRI-based 3D muscle reconstruction technique in 12 persons with a transfemoral amputation. All persons used a socket prosthesis and the time between primary amputation and inclusion ranged from 2 to 35 years. The volumes of the *m. gluteus maximus, m. gluteus medius, m. gluteus minimus, and m. tensor fasciae latae* in our study fell all within one standard deviation of the volumes found by Jaegers, Arendzen, and De Jongh (1995b). *M. piriformis* was not analyzed by Jaegers, Arendzen, and De Jongh (1995b). In contrast to Jaegers, Arendzen, and De Jongh (1995b), we found intramuscular adipose tissue in non-cleaved muscles, whereas they only found intramuscular adipose tissue in cleaved and non-fixed muscles.

Another important consideration is that the time between primary amputation and inclusion for our participant was 52 years. We expect the long-term use of a socket prosthesis to be the cause of the massive atrophy and increased adipose tissue in most muscles of the residual limb compared to the sound limb. Thus, whether muscle regeneration could be expected after such a long time of disuse remains questionable. Despite the age and length of post-amputation of this participant, we found an increase in muscle volume over time. This is promising for patients of lower age and for those with less time between primary amputation and inclusion.

Strengths and limitations

To our knowledge, this is the first study that used the MRI-based 3D muscle reconstruction technique using repeated measures and the first study that used this technique in a person with a bone-anchored prosthesis. The choice for a repeated measures design in this study is of added value because it allowed us to investigate the impact the intervention, in this case the bone-anchored prosthesis surgery in combination with rehabilitation, had on tissue level which has not been described in the literature previously. Because this was a single case study we were not able to examine the causal relationship between the intervention and the muscle volume change. It was remarkable that the trend of changes in muscle strength and changes in activity level was different from the trend shown in changes of muscle volume. The period of severe low back pain was potentially a confounding factor that influenced these trends. Future research in a larger cohort should investigate these correlations and should examine the causal relationship between the intervention and the muscle volume change. MRI-based 3D muscle reconstruction showed to be a safe and non-invasive method to obtain detailed information about the total volume of individual muscles. This in contrast to previously used methods to analyze the volume of the residual limb which were too invasive or too global such as: circumference measurement of the residual limb using a tape measures (Isakov, Burger, Gregoric, and Marincek, 1996; Renstrom, Grimby, Morelli, and Palmertz, 1983); and analyzing cross-sectional areas of muscles using ultrasonography (Schmalz, Blumentritt, and Reimers, 2001); muscle biopsy, computed tomography (Klingenstierna, Renstrom, Grimby, and Morelli, 1990; Renstrom, Grimby, Morelli, and Palmertz, 1983); or MRI (Jaegers, Arendzen, and De Jongh, 1995b; Putz et al., 2017). An additional advantage of the MRI-based 3D muscle reconstruction technique is that it can be used for finite element modeling (Portnoy et al., 2008).

An important limitation of our study is that feasibility was evaluated for only one type of metal implant. No adverse events were reported in all three MRI acquisitions; therefore, we may conclude that the use of 1.5T MRI in persons with a cobalt–chrome–molybdenum implant is safe and that the MRI-based 3D muscle reconstruction technique is feasible to assess muscle volume. However, it remains unknown whether MRI and the 3D muscle reconstruction technique are safe and feasible for bone-anchored prosthesis made with other metal alloys, such as titanium. Although titanium implants produces larger metal artifacts than cobalt–chrome–molybdenum implants (Panfili et al., 2014), research concerning titanium plates and screws suggests that the use of a 1.5T MRI scanner would be safe and the extent of metal artifacts can be minimized (Zou, Chu, Wang, and Hu, 2015). A second limitation is that we did not evaluate the muscle tissue composition, including the level and changes of intermuscular and intramuscular adipose tissue. Insight in the level of adipose tissue would be important because the latter is associated with decreased muscle performance and impaired physical function (Hilton et al., 2008). The influence of the increased BMI at both follow-up times compared to baseline on the change in muscle volume could not be interpreted because we did not analyze the muscle tissue composition and because this was a single case study. Presumably, a precise quantification of intermuscular and intramuscular adipose tissue would also increase the accuracy and thus the feasibility of the MRI-based 3D muscle reconstruction technique. Previous studies used the grey value (or image intensity) of subcutaneous adipose tissue to identify the intermuscular and intramuscular adipose tissue within T1-weighted MR images (Gallagher et al., 2005; Hilton et al., 2008). The validity of this method is questionable, as also other tissues (i.e., blood, trabecular bone, and mineralization) besides fat appear hyper-intense on T1-weighted MR images. Specific MRI sequences suitable for the discrimination of water and fat content, such as the DIXON MRI sequence (Baudin et al., 2015), probably lead to a more accurate method to identify the level of intermuscular and intramuscular adipose tissue. As a third limitation, we report the amount of manual correction necessary during the semi-automatic segmentation, which was partly due to the large amount of adipose tissue present. This may have caused potential measurement bias and decreased accuracy. To minimize these aspects and retain accuracy, we used consensus meetings which in turns limited the feasibility as they were time-consuming. Another possible cause of the amount of mandatory manual correction is that a student performed the manual segmentation of the baseline MRI instead of an experienced radiologist. We selected a student for this task because this part of the analysis is the most time-intensive. A final limitation was that it was not possible to distinguish whether the changes to the muscle volume were attributed solely to the change of type of attachment or the rehabilitation program or because of the combination. In our clinical practice, bone-anchored prosthesis surgery is always followed by a standardized rehabilitation program focusing on improvement of hip abductor strength, core stability, and gait quality (Leijendekkers, van Hinte, Nijhuis-van der Sanden, Staal, 2017). To investigate the influence of the rehabilitation on the results future studies could include a control group of persons with socket attached prostheses.

Recommendation for future research

Future research should focus on improvement of the accuracy of the 3D muscle reconstruction technique, options to quantify adipose tissue and to increase the practical applicability. The MRI-based 3D muscle reconstruction technique will be more practical if it is less time-intensive and less or no manual correction is necessary within the analysis process.

The 3D muscle reconstruction is of added value because it can give insight in the impact of interventions on tissue level. This is relevant within the discussion concerning the inclusion criteria for bone-anchored prosthetic surgery. To date, the time of the onset of muscle atrophy and increase of adipose tissue is not clear. Furthermore, there is a lack of knowledge concerning the extent of potential reversibility of the atrophic process as a result of a bone-anchored prosthesis use. Future research should focus on both aspects in a larger repeated measures study with persons with a bone-anchored prosthesis, in which stratification of the time between primary amputation and bone-anchored prosthesis surgery is implemented.

Conclusion

MRI-based 3D muscle reconstruction technique appears to be feasible to assess hip abductor muscle volume in a person with a cobalt–chrome–molybdenum bone-anchored prosthesis in an experimental setting. The repeated measures design allowed us to investigate the impact of the intervention on tissue level. In our participant, the majority of hip abductor muscles increased in volume at 6-month and 12-month follow-up relative to baseline. The accuracy of the technique was potentially negatively influenced by severe intermuscular and intramuscular adipose tissue. Future research should focus on further automation of the 3D reconstruction technique, the analysis of muscle tissue composition, and the feasibility of 3D muscle reconstruction for bone-anchored implants made with other commonly used metallic alloys.

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Declaration of Interest

The authors report no conflict of interest.

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